Search for decoherence and CPT violation in the B meson system at a B-factory

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CPT: introduction

The three discrete symmetries of QM, C (charge conjugation), P (parity), and T (time reversal) are known to be violated in nature both singly and in pairs. Only CPT appears to be an exact symmetry of nature.

CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):
Exact CPT invariance holds for any quantum field theory (flat space-time) which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

Extension of CPT theorem to a theory of quantum gravity far from obvious (e.g. CPT violation appears in some models with space-time foam backgrounds).

No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

CPT: introduction

Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

Neutral meson systems are the most intriguing systems in nature; they offer unique possibilities to test CPT invariance;

e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system $\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$

neutral B system $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

1) “Standard” tests of CPT symmetry in the neutral B system

neutral B meson system: “standard” picture

Time dependence of Quark-Flavor Oscillations given by Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \mu_{ik}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \left[\begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

Effective Hamiltonian has 8 real parameters

m_{ik} and Γ_{ik} hermitian

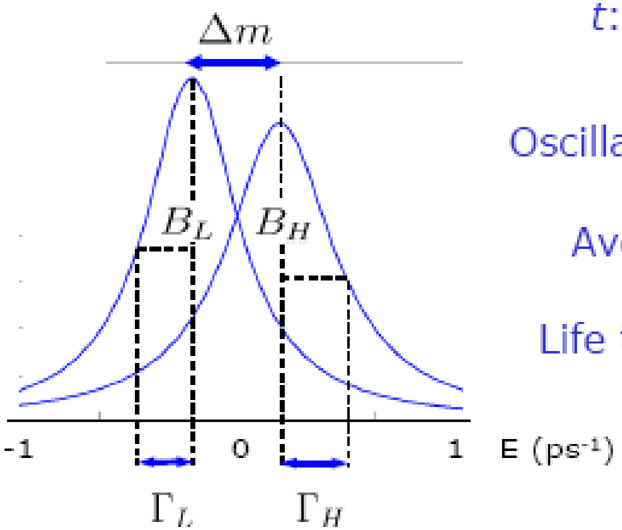
If CPT holds, $m_{11}=m_{22}$, $\Gamma_{11}=\Gamma_{22}$, and

$$B^0_L(t) = \left(pB^0 + q\overline{B}^0\right)\cdot e^{-\gamma_L t}, \quad \gamma_L = i\, m_L + \Gamma_L / 2,$$

$$B^0_H(t) = \left(pB^0 - q\overline{B}^0\right)\cdot e^{-\gamma_H t}, \quad \gamma_H = i\, m_H + \Gamma_H / 2.$$

t: B meson proper time

6 real parameters, only 5 observable (arbitrary phases): m_{11}, Γ_{11}, Re(m_{12}), Im(m_{12}), Re(Γ_{12}), Im(Γ_{12})



Oscillation frequency $\Delta m \equiv m_H - m_L \approx 0.5\,\mathrm{ps}^{-1}$ *Well measured*

Average life time $1/\Gamma \approx 1.6\,\mathrm{ps}$ *Well measured*

Life time difference $\Delta\Gamma \equiv \Gamma_H - \Gamma_L \ll 1$ ***NOT** well measured*

$\Delta m/\Delta\Gamma \sim -200$ in QCD lattice calc. from A. Lusiani

CPT violation in the neutral B system: "standard" picture

If CPT violated, also two eigenstates B_L, B_H with

CPT and CP violation

$$\Delta m \equiv m_H - m_L \approx 2|M_{12}| \,,$$
$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L \approx 2|M_{12}|\, \mathrm{Re}(\Gamma_{12}/M_{12})$$

$$m \equiv \frac{1}{2}(M_{11}+M_{22}) \,, \quad \Gamma \equiv \frac{1}{2}(\Gamma_{11}+\Gamma_{22}) \,,$$
$$\delta m \equiv M_{11} - M_{22} \,, \quad \delta\Gamma \equiv \Gamma_{11} - \Gamma_{22} \,.$$

$$\left|\frac{q}{p}\right|^2 \approx 1 - \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$$

T and CP violation

$$z \equiv \frac{\delta m - \frac{i}{2}\delta\Gamma}{2\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right) + \frac{1}{4}\left(\delta m - \frac{i}{2}\delta\Gamma\right)^2}} = \frac{\delta m - \frac{i}{2}\delta\Gamma}{\Delta m - \frac{i}{2}\Delta\Gamma} \,. \qquad (7)$$

Definition of |q/p| as with CPT conservation, but B_L, B_H given by p, q, <u>and z</u>

z = - 2δ (ε,δ Kaon formalism)
z = - cosθ (DEθφ formalism)

Eigenstates proper-time evolution:

$$B_L^0(t) = \left[p\cdot\sqrt{1-z}\cdot B^0 + q\cdot\sqrt{1+z}\cdot\overline{B}^0\right]\cdot e^{-\gamma_L t}$$
$$B_H^0(t) = \left[p\cdot\sqrt{1+z}\cdot B^0 - q\cdot\sqrt{1-z}\cdot\overline{B}^0\right]\cdot e^{-\gamma_H t}$$

from A. Lusiani

CPT asymmetries with inclusive dilepton events

Decay rates of neutral B meson pairs to $\ell^+\ell^+$, $\ell^-\ell^-$, and $\ell^+\ell^-$ events to first-order in z:

$$N^{++} \propto e^{-\Gamma|\Delta t|}|p/q|^2\{\cosh(\Delta\Gamma\Delta t/2)-\cos(\Delta m\Delta t)\}$$
$$N^{--} \propto e^{-\Gamma|\Delta t|}|q/p|^2\{\cosh(\Delta\Gamma\Delta t/2)-\cos(\Delta m\Delta t)\}$$
$$N^{+-} \propto e^{-\Gamma|\Delta t|}\{\cosh(\Delta\Gamma\Delta t/2)+\cos(\Delta m\Delta t)-2\,\mathrm{Re}\,z\sinh(\Delta\Gamma\Delta t/2)+2\,\mathrm{Im}\,z\sin(\Delta m\Delta t)\}$$

Asymmetries from same-sign and opposite-sign events:

$$A_{T/CP} = \frac{P(\bar{B}^0\to B^0)-P(B^0\to\bar{B}^0)}{P(\bar{B}^0\to B^0)+P(B^0\to\bar{B}^0)} = \frac{N^{++}-N^{--}}{N^{++}+N^{--}} = \frac{1-|q/p|^4}{1-|q/p|^4}$$

$$A_{CPT/CP}(\Delta t) = \frac{P(B^0\to B^0)-P(\bar{B}^0\to\bar{B}^0)}{P(B^0\to B^0)+P(\bar{B}^0\to\bar{B}^0)} = \frac{N^{+-}(\Delta t>0)-N^{+-}(\Delta t<0)}{N^{+-}(\Delta t>0)+N^{+-}(\Delta t<0)}$$
$$\simeq 2\frac{-\mathrm{Re}\,z\sinh(\Delta\Gamma\Delta t/2)+\mathrm{Im}\,z\sin(\Delta m\Delta t)}{\cosh(\Delta\Gamma\Delta t/2)+\cos(\Delta m\Delta t)}$$

- small $\Delta\Gamma$ gives $\mathrm{Re}\,z\sinh(\Delta\Gamma\Delta t/2)\simeq\Delta\Gamma\times\mathrm{Re}\,z\times(\Delta t/2)$ — measure $\Delta\Gamma\times\mathrm{Re}\,z$
- $\Delta t\equiv$ difference of proper decay times $=t^+-t^-$ for $\ell^+\ell^-$ events
- maximum likelihood fit to sum of PDFs with decay rates for signal & background events
- $\ell^+\ell^+$, $\ell^-\ell^-$: corrections for charge asymmetries in lepton reconstruction/identification

from A. Lusiani

CPT asymmetries with inclusive dilepton events

$B^0\overline{B}^0$ Mixing Incl. Dilepton Events

BELLE

$29.4\ \mathrm{fb}^{-1}$

PRD 67, 052004 (2003)

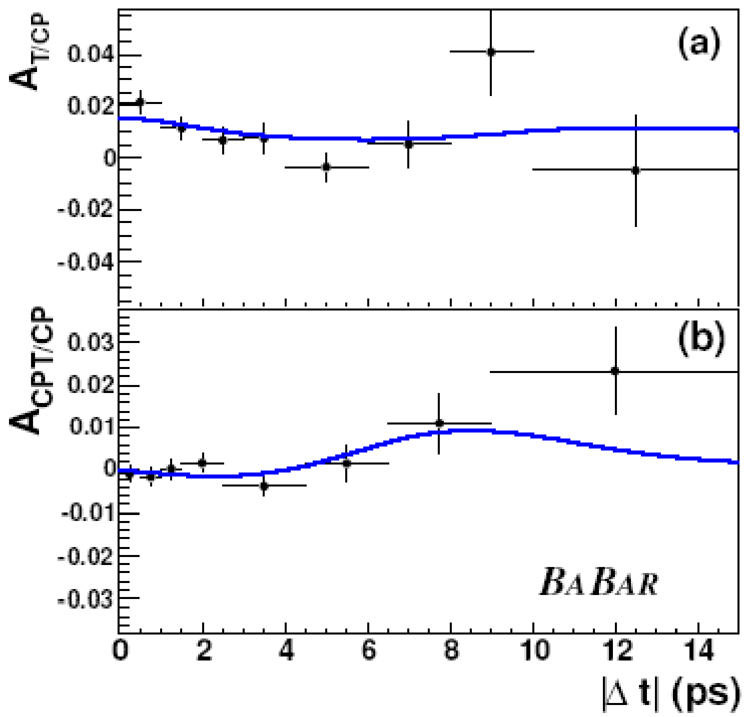
- measures opposite-sign Δt-odd di-lepton asymmetry
- $\mathrm{Re}(z) = [0 \pm 120\,(\mathrm{stat.}) \pm 10\,(\mathrm{syst.})]\cdot 10^{-3}$ $\mathrm{Im}(z) = [30 \pm 10\,(\mathrm{stat.}) \pm 30\,(\mathrm{syst.})]\cdot 10^{-3}$

$B^0\overline{B}^0$ Mixing w. Inclusive Dileptons

BABAR

$232\ \mathrm{fb}^{-1}$

PRL 96, 251802 (2006)



same-sign time-integrated di-lepton asymmetry

opposite-sign Δt-odd di-lepton asymmetry

$|q/p| - 1 = [-0.8 \pm 2.7\,(\mathrm{stat.}) \pm 1.9\,(\mathrm{syst.}]\cdot 10^{-3}$

$\mathrm{Im}(z) = [-13.9 \pm 7.3\,(\mathrm{stat.}) \pm 3.2\,(\mathrm{syst.})]\cdot 10^{-3}$

$\Delta\Gamma \cdot \mathrm{Re}(z) = [-7.1 \pm 3.9\,(\mathrm{stat.}) \pm 2.0\,(\mathrm{syst.})]\cdot 10^{-3}$

B vs K mesons

$$z = -2\delta = \frac{\delta m - (i/2)\delta\Gamma}{\Delta m + i\Delta\Gamma/2}$$

B meson system

K meson system

from Bell-Steinberger relation

Im z =(−13.9 ± 7.3 ± 3.2) × 10^{-3}

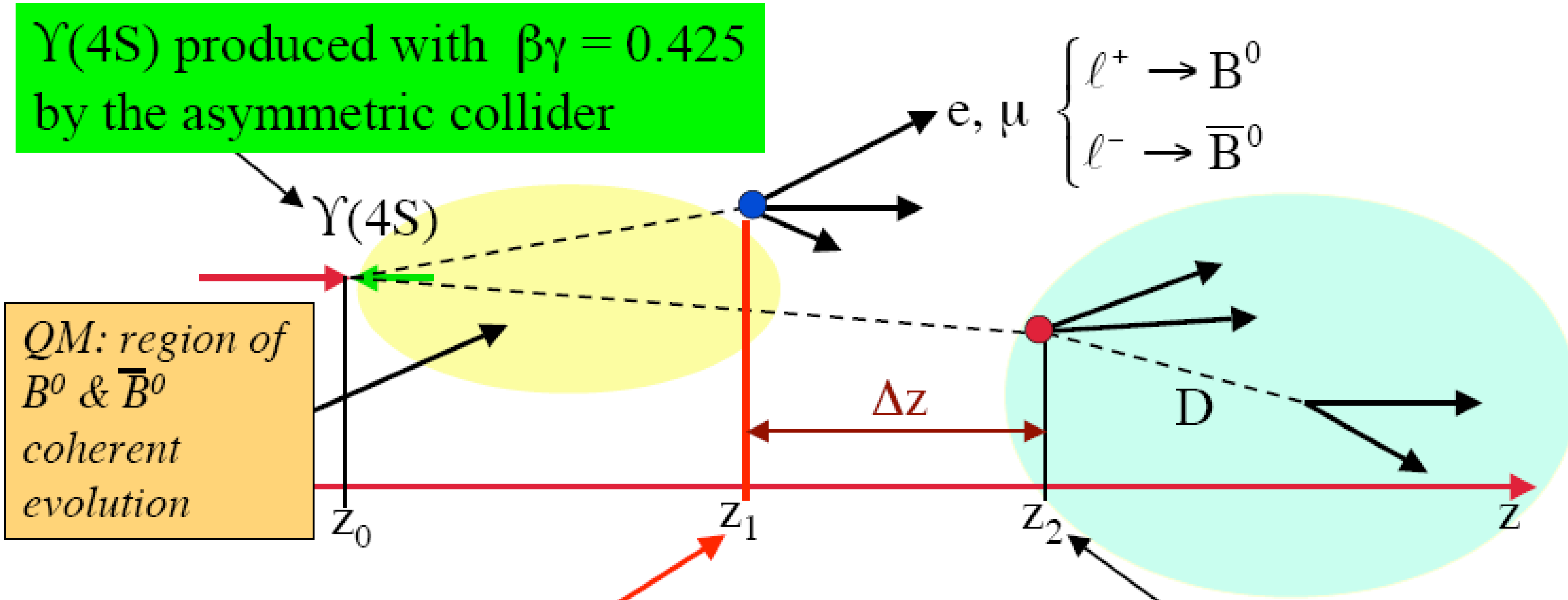
Im δ =(−0.1 ± 1.4) × 10^{-5}

$$\Delta m \cong 3.3\times 10^{-13} \ \ \mathrm{GeV}$$
$$\Delta\Gamma << \Delta m$$

$$\Delta m \cong 3.5\times 10^{-15} \ \ \mathrm{GeV}$$
$$\Delta\Gamma \cong 7.3\times 10^{-15} \ \ \mathrm{GeV}$$

2) Search for decoherence and CPT violation in the neutral B meson system

Correlated B meson pairs



B^0 and $\overline{B}^0$ oscillate coherently. When the first decays, the other is known to be of the opposite flavour, at the same proper time

Than the other B^0 oscillates freely before decaying after a time given by

$$\Delta t \approx \Delta z / c\beta\gamma$$

N.B. : production vertex position z_0 not very well known : only Δz is available !

QM predictions for entangled pairs

Time (Δt)-dependent decay rate into two **O**pposite **F**lavour (OF) states

$$R_{OF} \propto e^{-\Gamma(t_1+t_2)}(1+\cos(\Delta m_d \Delta t))$$

Δm_d is the mass difference of the two mass eigenstates

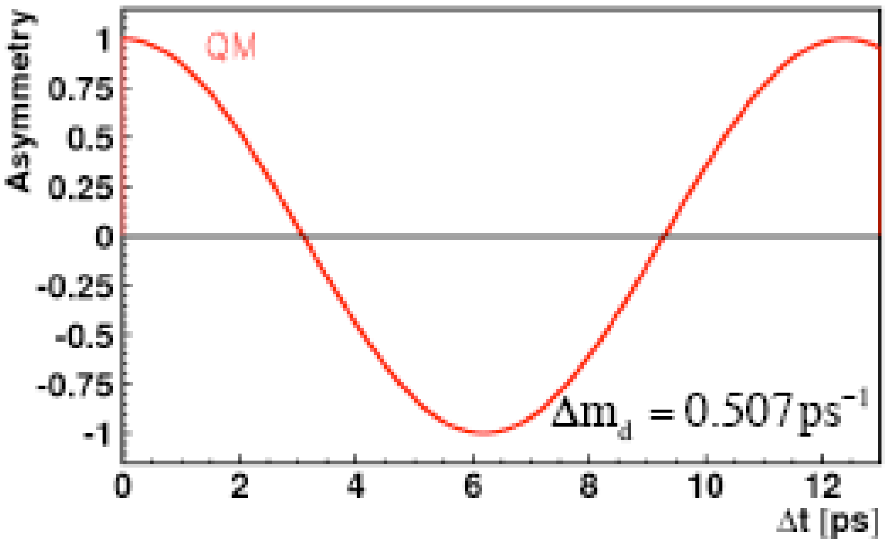
idem, into two **S**ame **F**lavour (SF) states

$$R_{SF} \propto e^{-\Gamma(t_1+t_2)}(1-\cos(\Delta m_d \Delta t))$$

=> we obtain the

time-dependent asymmetry

$$A_{QM}(\Delta t) = \frac{R_{OF} - R_{SF}}{R_{OF} + R_{SF}}(\Delta t) = \cos(\Delta m_d \Delta t)$$

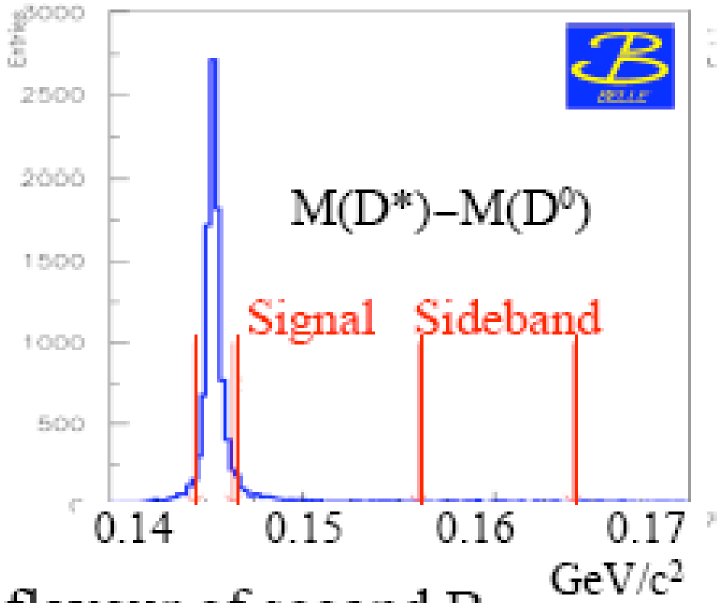


(ignoring CP violation effects $O(10^{-4})$, and taking $\Gamma_H = \Gamma_L$)

from A. Bay

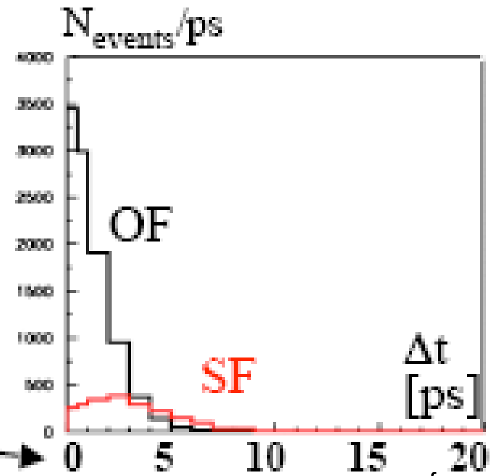
Events selection and tagging

- First B measured via
  $B^0 \to D^{*-} \ell^+ \nu$
  $\hookrightarrow \overline{D}^0 \pi^-_{slow}$
  - $\hookrightarrow K^+\pi^-$
  - $\hookrightarrow K^+\pi^-\pi^0$
  - $\hookrightarrow K^+\pi^-\pi^+\pi^-$



- Remaining tracks are used to guess the flavour of second B, from the standard Belle flavour tagging procedure

From a total of 152 10^6 $B^0\overline{B}^0$ pairs: ~150 fb^{-1}
– 6718 OF and 1847 SF events after selection.
– Δz is obtained from track fit of the two vertices and converted into a Δt value

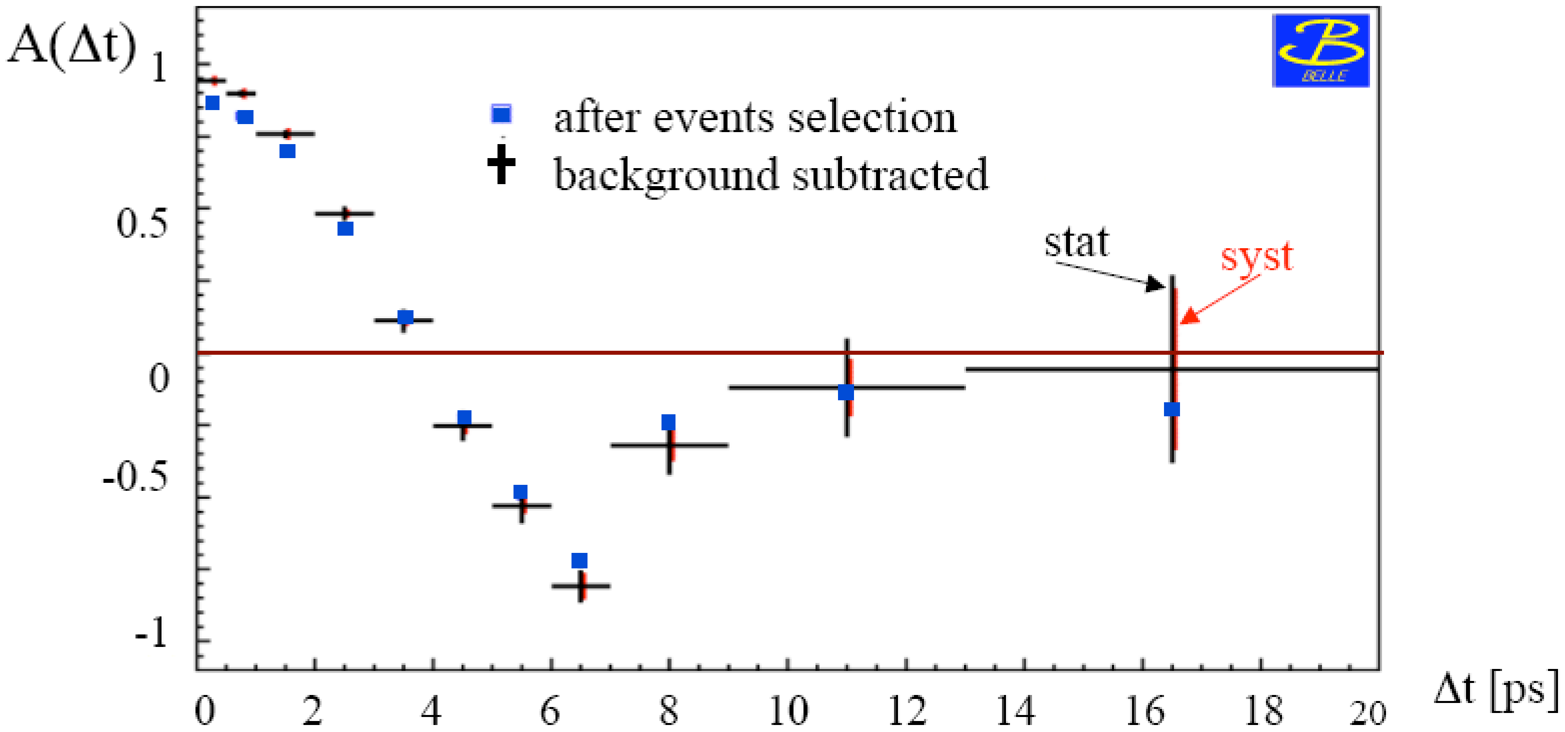


from A. Bay

Time dependent asymmetry

We correct bin by bin the OF and SF distributions for

- Fake D* background
- Uncorrelated D*-leptons, mainly D* and leptons from different B^0
- $B^{\pm} \rightarrow D^{**} \, l \, \nu$ background
- ~1.5% fraction of wrong flavour associations



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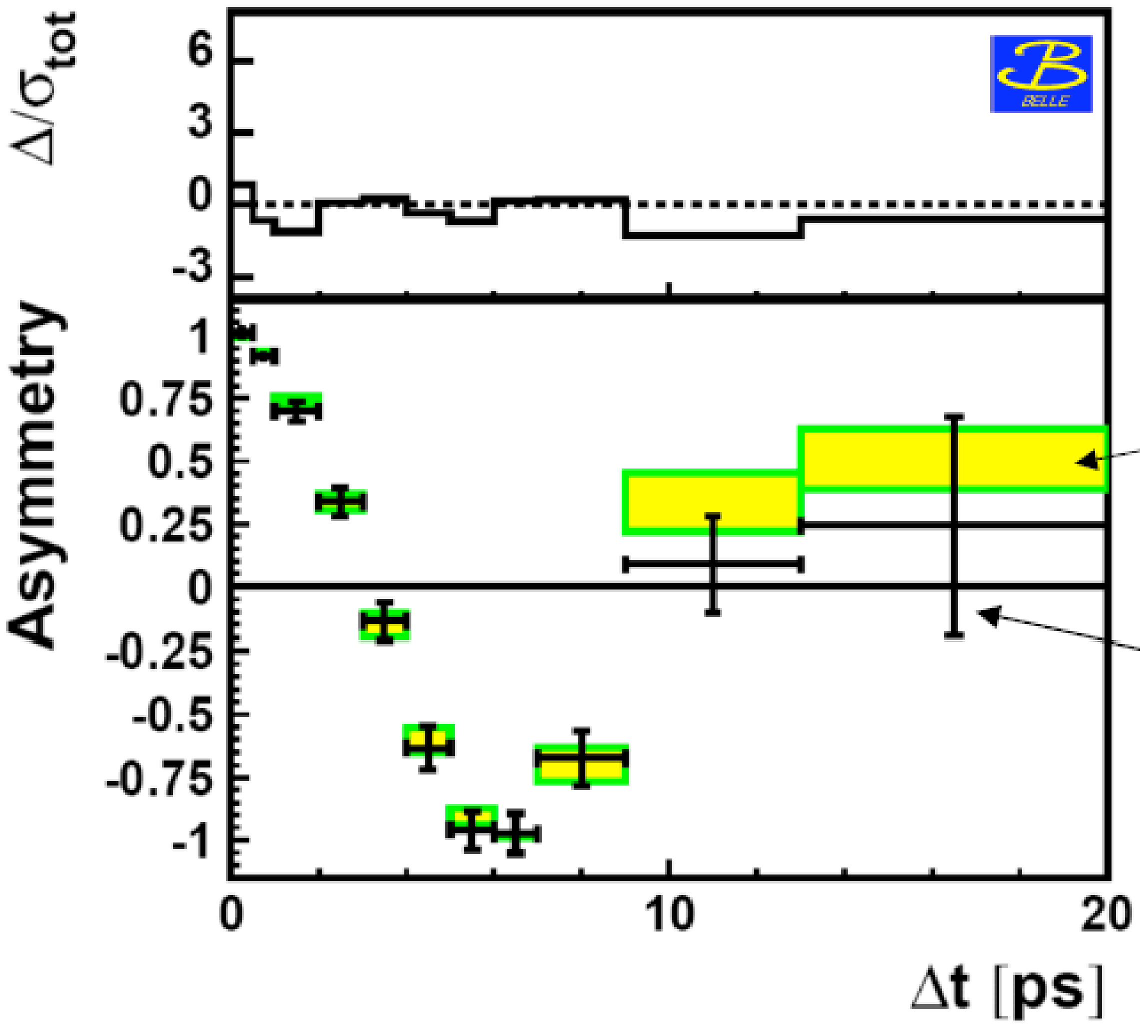
Time dependent asymmetry

After correcting for Δt resolution and selection efficiency by a deconvolution procedure:



fitted value:

$\Delta m_d = (0.501 \pm 0.009)\ ps^{-1}$

$\chi^2 = 5.2$ (11 dof)

QM (error from Δm_d)

Data

=> Data fits QM

PRL 99 131802 (2007)

from A. Bay

Time dependent asymmetry

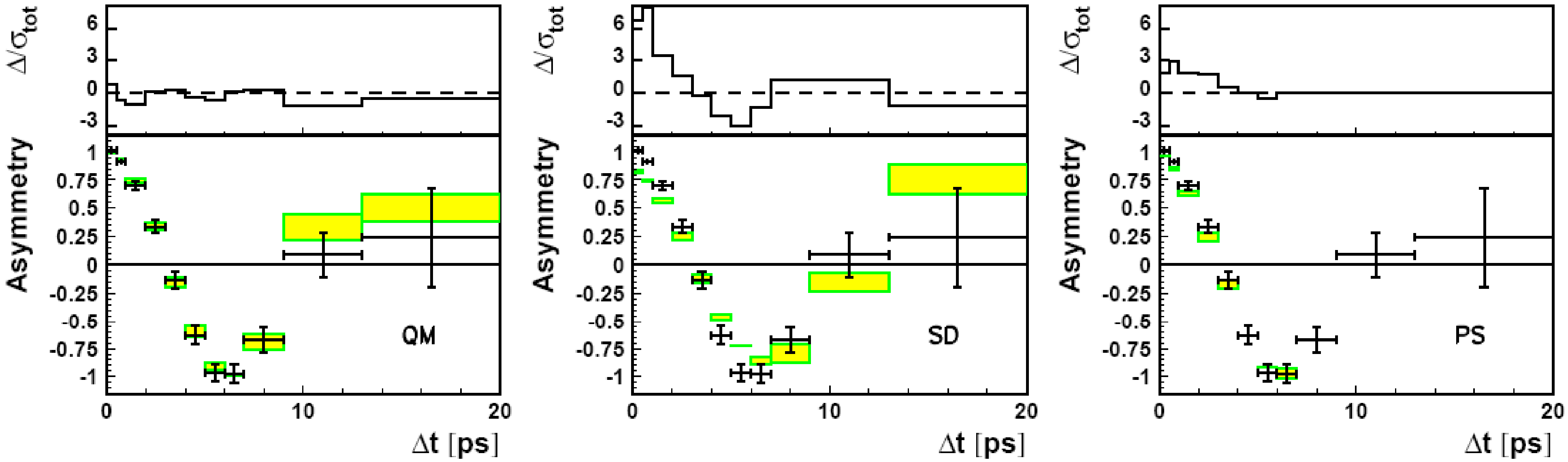


Figure 3: Bottom: time-dependent flavour asymmetry (crosses) and the results of weighted least-squares fits to the (left to right) QM, SD, and PS models (rectangles, showing $\pm 1\sigma$ errors on Δm_d). Top: differences $\Delta \equiv A_{\rm data} - A_{\rm model}$ in each bin, divided by the total experimental error $\sigma_{\rm tot}$. Bins where $\mathrm{A}_{\rm PS}^{\rm min} < A_{\rm data} < \mathrm{A}_{\rm PS}^{\rm max}$ have been assigned a null deviation: see the text.

PRL 99 131802 (2007)

Test of quantum coherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|B^0\rangle |\overline{B}^0\rangle - |\overline{B}^0\rangle |B^0\rangle \right]$$

$$I(f_1, f_2; \Delta t) = \tfrac{N}{2}\Big[\left|\langle f_1, f_2 | B^0 \overline{B}^0(\Delta t)\rangle\right|^2 + \left|\langle f_1, f_2 | \overline{B}^0 B^0(\Delta t)\rangle\right|^2$$

$$-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\langle f_1, f_2 | B^0 \overline{B}^0(\Delta t)\rangle \langle f_1, f_2 | \overline{B}^0 B^0(\Delta t)\rangle^*\right)\Big]$$

Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \rightarrow \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \rightarrow \quad$ total decoherence

(also known as Furry's hypothesis or spontaneous factorization) [W.Furry, PR 49 (1936) 393]

> Feynman described the phenomenon of interference as containing "the only mistery" of quantum mechanics

Special case if ζ=0

(totally destructive QM interference):

$$I(f, f; \Delta t = 0) = 0$$

A simple model for decoherence

The decoherence parameter ζ depends on the basis in which the spontaneous factorization mechanism is specified:

$$\left[|B_H\rangle |B_L\rangle - |B_L\rangle |B_H\rangle \right] \quad \Rightarrow \quad |B_H\rangle |B_L\rangle \quad \text{or} \quad |B_L\rangle |B_H\rangle$$

$$\left[|B^0\rangle |\overline{B}^0\rangle - |\overline{B}^0\rangle |B^0\rangle \right] \quad \Rightarrow \quad |B^0\rangle |\overline{B}^0\rangle \quad \text{or} \quad |\overline{B}^0\rangle |B^0\rangle$$

For a generic basis $\{B_\alpha, B_\beta\}$ we can write:

$$I(f_1,t_1; f_2,t_2) = \frac{N'}{2} \Big[\left| \langle f_1 | B_\alpha(t_1)\rangle \langle f_2 | B_\beta(t_2)\rangle \right|^2 + \left| \langle f_1 | B_\beta(t_1)\rangle \langle f_2 | B_\alpha(t_2)\rangle \right|^2$$
$$- 2 \cdot (1 - \zeta_{\alpha,\beta})\, \Re\left(\langle f_1 | B_\beta(t_1)\rangle \langle f_2 | B_\alpha(t_2)\rangle \langle f_1 | B_\alpha(t_1)\rangle^* \langle f_2 | B_\beta(t_2)\rangle^* \right) \Big]$$

(for QM the result is independent on any the basis choice)

Test of quantum coherence

1) Decoherence in B_H, B_L : $A \sim (1-\zeta_{BHBL}) A_{QM}$

$\zeta_{BHBL} = 0.004 \pm 0.017$ (preliminary)

in K system (KLOE FINAL) :

$$\zeta_{SL} = \left(0.3 \pm 1.8_{STAT} \pm 0.6_{SYST}\right) \times 10^{-2}$$

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2) Decoherence in B^0, $\overline{B}^0$: $A \sim (1-\zeta_{B^0\overline{B}^0}) A_{QM} + \zeta_{B^0\overline{B}^0} A_{SD}$

$\zeta_{B^0\overline{B}^0} = 0.029 \pm 0.057$

$A_{QM}(\Delta t) = \cos(\Delta m_d \Delta t)$

in K system (KLOE FINAL):

$$\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}\right) \times 10^{-7}$$

A_{SD} = integration in t1+t2 of

$$A_{SD}(t_1, t_2) = \cos(\Delta m_d t_1) \cos(\Delta m_d t_2)$$

obs. in CPV decay channel => terms $\zeta_{00}/|\eta_{+-}|^2$ => high sensitivity to $\zeta_{0\bar{0}}$

K system $\dfrac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \eta_{+-} = \dfrac{1-\lambda_{+-}}{1+\lambda_{+-}} << 1$ B system $\dfrac{A(B_H \to f_{CP})}{A(B_L \to f_{CP})} = \eta_{f_{CP}} = \dfrac{1-\lambda_{f_{CP}}}{1+\lambda_{f_{CP}}}$; $\Im \lambda_{\psi K} = 0.68$

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=1.5 fb^{-1} (2004-05 data)
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L , Δm fixed from PDG

KLOE FINAL:

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}) \times 10^{-7}$$

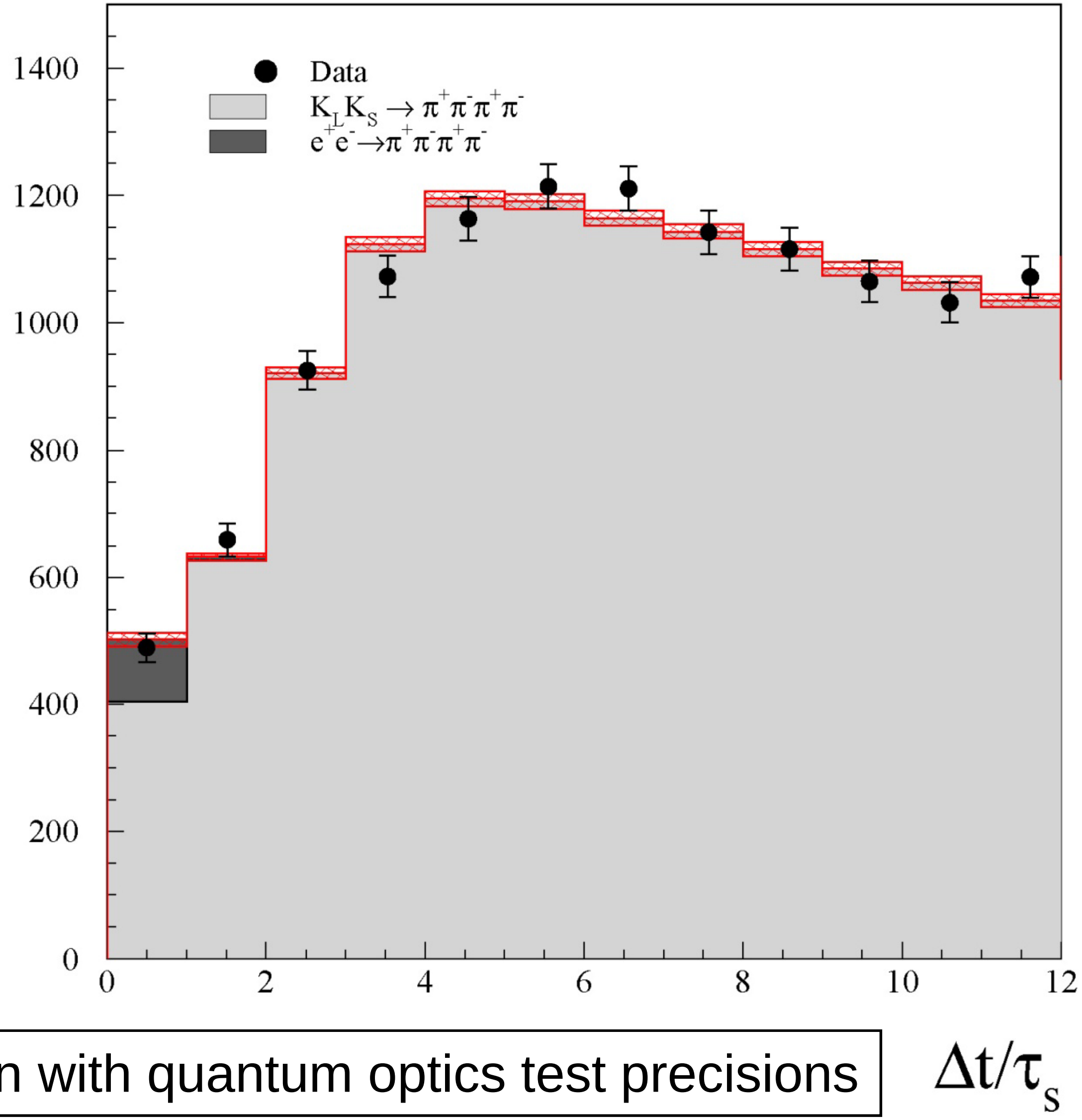
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain:

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



Comparison with quantum optics test precisions

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

The decoherence parameter ζ depends on the basis in which the spontaneous factorization mechanism is specified (Bertlmann et al. PR D60 (1999) 114032) :

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right] = \frac{N}{\sqrt{2}}\left[|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right]$$

$$I(\pi^+\pi^-, \pi^+\pi^-; |\Delta t|) \propto \left\{e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2\cdot(1-\zeta_{SL})\cdot e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos(\Delta m|\Delta t|)\right\}$$

Decoherence parameter:

$\zeta_{SL} = 0 \quad \to \quad$ QM

$\zeta_{SL} = 1 \quad \to \quad$ total decoherence

- Analysed data: 1.5 fb^{-1} (2004-05 data)

KLOE FINAL :

$$\zeta_{SL} = (0.3 \pm 1.8_{STAT} \pm 0.6_{SYST}) \times 10^{-2}$$

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain :

$$\zeta_{SL} = 0.13 \pm 0.16$$

In the B-meson system, BELLE coll. obtains (preliminary):

$$\zeta_{HL}^{B} = 0.004 \pm 0.017$$

Decoherence and CPT violation

Modified Liouville – von Neumann equation for the density matrix of the kaon system:

$$\dot{\rho}(t) = \underbrace{-iH\rho + i\rho H^{+}}_{\text{QM}} + L(\rho)$$

extra term inducing decoherence:
pure state => mixed state

<u>Possible decoherence due quantum gravity effects:</u>

Black hole information loss paradox => Possible decoherence near a black hole.

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically <u>space-time foam</u>) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

J. Ellis et al.[3-6] => model of decoherence for neutral kaons => 3 new CPTV param. α,β,γ:

$$L(\rho) = L(\rho;\alpha,\beta,\gamma)$$
$$\alpha,\gamma > 0 \quad , \quad \alpha\gamma > \beta^2$$

At most: $\alpha,\beta,\gamma = O\left(\frac{M_K^{\;2}}{M_{PLANCK}}\right) \approx 2\times10^{-20}\ \text{GeV}$

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: decoherence & CPTV by QG

Study of time evolution of **single kaons** decaying in $\pi+\pi-$ and semileptonic final state

CPLEAR PLB 364, 239 (1999)

$$\alpha = (-0.5 \pm 2.8)\times 10^{-17}\ \text{GeV}$$
$$\beta = (2.5 \pm 2.3)\times 10^{-19}\ \text{GeV}$$
$$\gamma = (1.1 \pm 2.5)\times 10^{-21}\ \text{GeV}$$

Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.

In the complete positivity hypothesis

$\alpha = \gamma$, $\beta = 0$

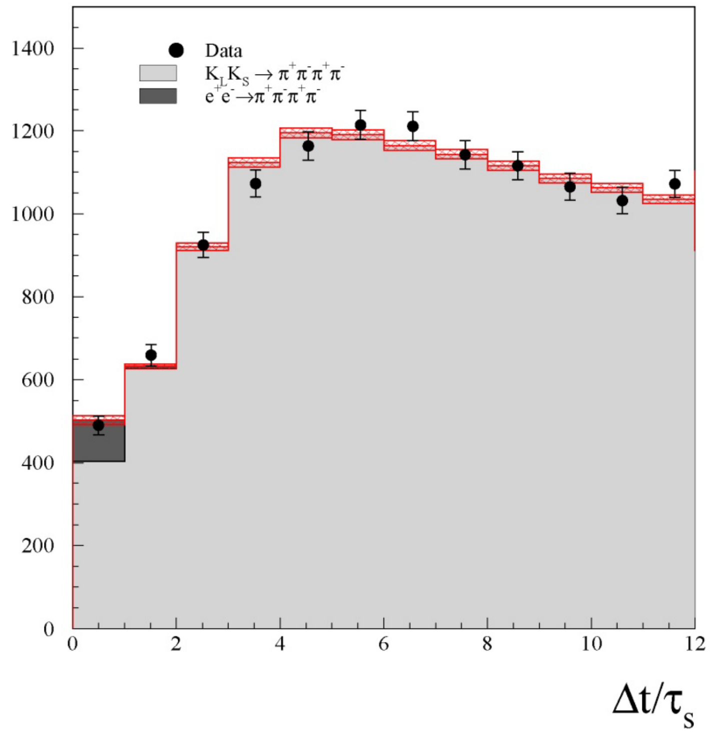
=> only one independent parameter: γ

The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\gamma)$ gives:

KLOE FINAL L=1.5 fb^{-1}

$$\gamma = (0.7 \pm 1.2_{STAT} \pm 0.3_{SYST})\times 10^{-21}\ \text{GeV}$$

terms $\gamma/(\Delta\Gamma\ |\eta_{+-}|^2)$



decoherence & CPTV by QG

Formalism of α,β,γ could be extended to B mesons (to be done):

$$L(\rho) = L(\rho;\alpha,\beta,\gamma)$$

$$\alpha,\gamma > 0 \quad , \quad \alpha\gamma > \beta^2$$

At most: $\alpha,\beta,\gamma = O\left(\frac{M_B{}^2}{M_{PLANCK}}\right) \approx 2\times10^{-18}$ GeV

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$: CPT violation in correlated K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$|i\rangle \propto \left(K^0\overline{K}^0 - K^0\overline{K}^0\right) + \omega\left(K^0\overline{K}^0 + K^0\overline{K}^0\right)$$

$$\propto \left(K_S K_L - K_L K_S\right) + \omega\left(K_S K_S - K_L K_L\right)$$

at most one expects: $|\omega|^2 = O\left(\frac{E^2 / M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$

In some microscopic models of space-time foam arising from non-critical string theory:
[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014] $|\omega| \sim 10^{-4} \div 10^{-5}$

The maximum sensitivity to ω is expected for $f_1 = f_2 = \pi^+\pi^-$
All CPTV effects induced by QG (α,β,γ,ω) could be simultaneously disentangled.

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: CPT violation in correlated K states

Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$:

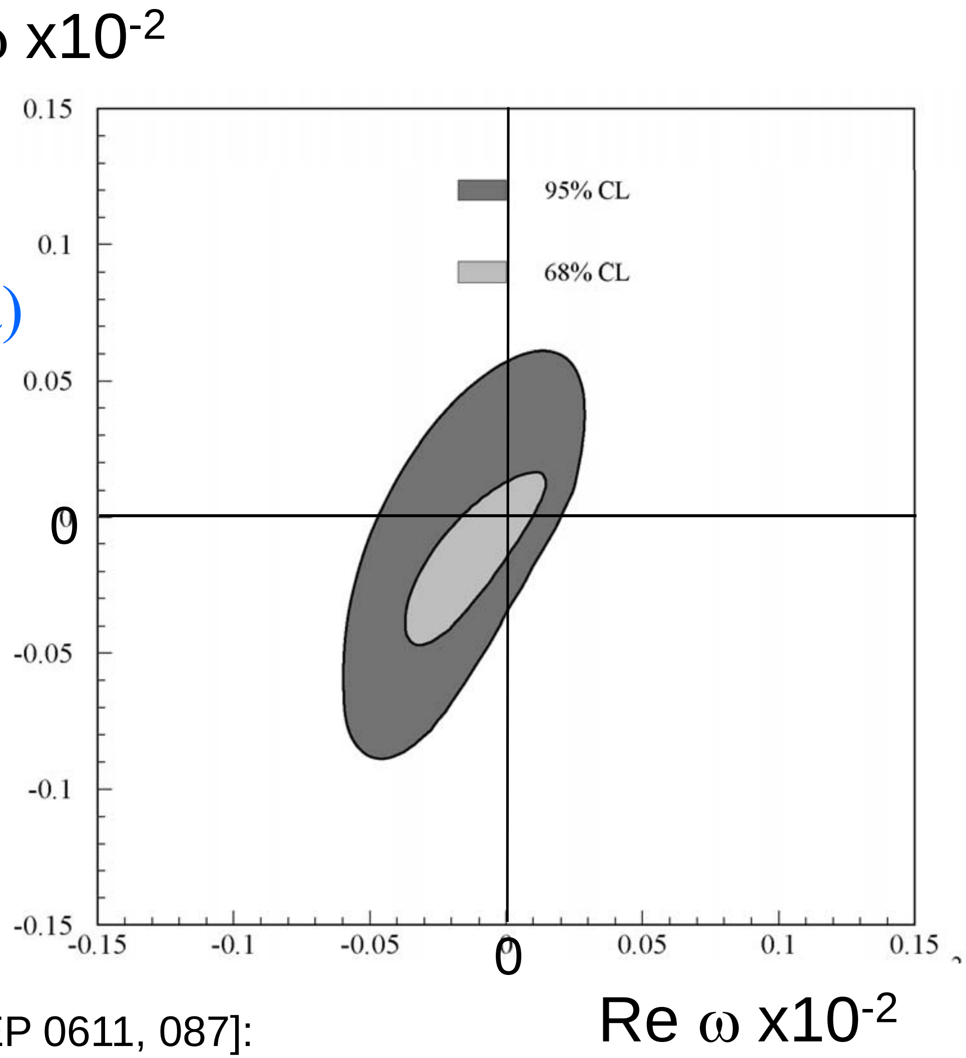
• Analysed data: 1.5 fb^{-1} (2004-05 data)

KLOE FINAL :

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\,\text{C.L.}$$



In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

$$-0.0084 \le \Re\omega \le 0.0100 \quad \text{at } 95\%\,\text{C.L.}$$

CPT violation and decoherence in B meson states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the B meson state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$|i\rangle \propto \left(B^0\overline{B}^0 - B^0\overline{B}^0\right) + \omega\left(B^0\overline{B}^0 + B^0\overline{B}^0\right)$$

EquaL-Sign di-lepton charge asymmetry Δt dependence

ALVAREZ, BERNABEU, NEBOT

❖ **Interesting tests of the ω-effect can be performed by looking at the equal-sign di-lepton decay channels**

a first decay $B \to X\ell^{\pm}$ and a second decay, Δt later, $B \to X'\ell^{\pm}$

$$A_{sl} = \left.\frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)}\right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathcal{O}((Re\ \varepsilon)^2)$$

$$\omega = |\omega| e^{i\Omega} \quad \Rightarrow \quad I(\ell^{\pm},\ell^{\pm},\Delta t = 0) \sim |\omega|^2$$

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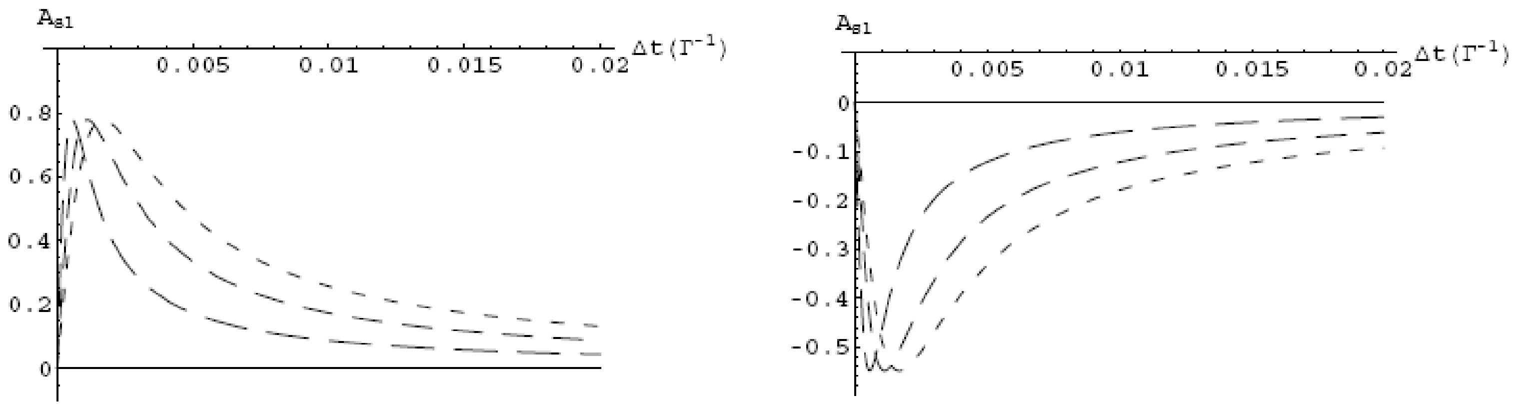
Equal sign di-lepton time asymmetry

- For ω=0 equal sign di-lepton time asymmetry A_{sl} is exactly time independent
- For $\omega \neq 0$ A_{sl} acquire a time dependence

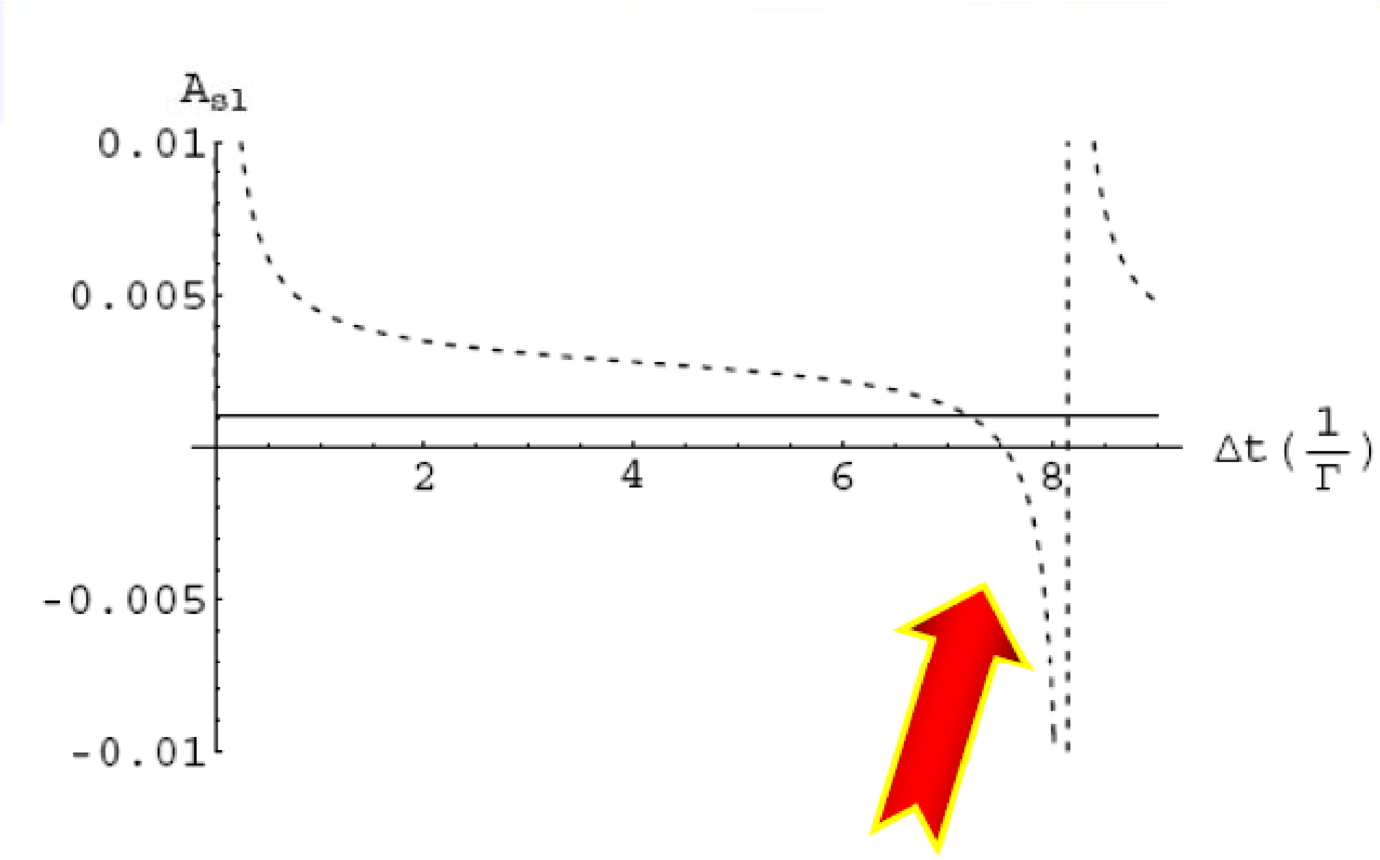


(a) $\Omega = 0$ (b) $\Omega = \frac{3}{2}\pi$

Figure 6.2: Equal-sign dilepton charge asymmetry for different values of ω; $|\omega| = 0$ (solid line), $|\omega| = 0.0005$ (long-dashed), $|\omega| = 0.001$ (medium-dashed), $|\omega| = 0.0015$ (short-dashed). When $\omega \neq 0$ a peak of height $A_{sl}(peak) = 0.77\cos(\Omega)$ appears at $\Delta t(peak) = 1.12\,|\omega|\,\frac{1}{\Gamma}$, producing a drastic difference, in particular in its time dependence. Observe that the peak, independently of the value of $|\omega|$, can reach enhancements of order 10^3 the value of the asymmetry when $\omega = 0$.

From
E. Alvarez PhD thesis

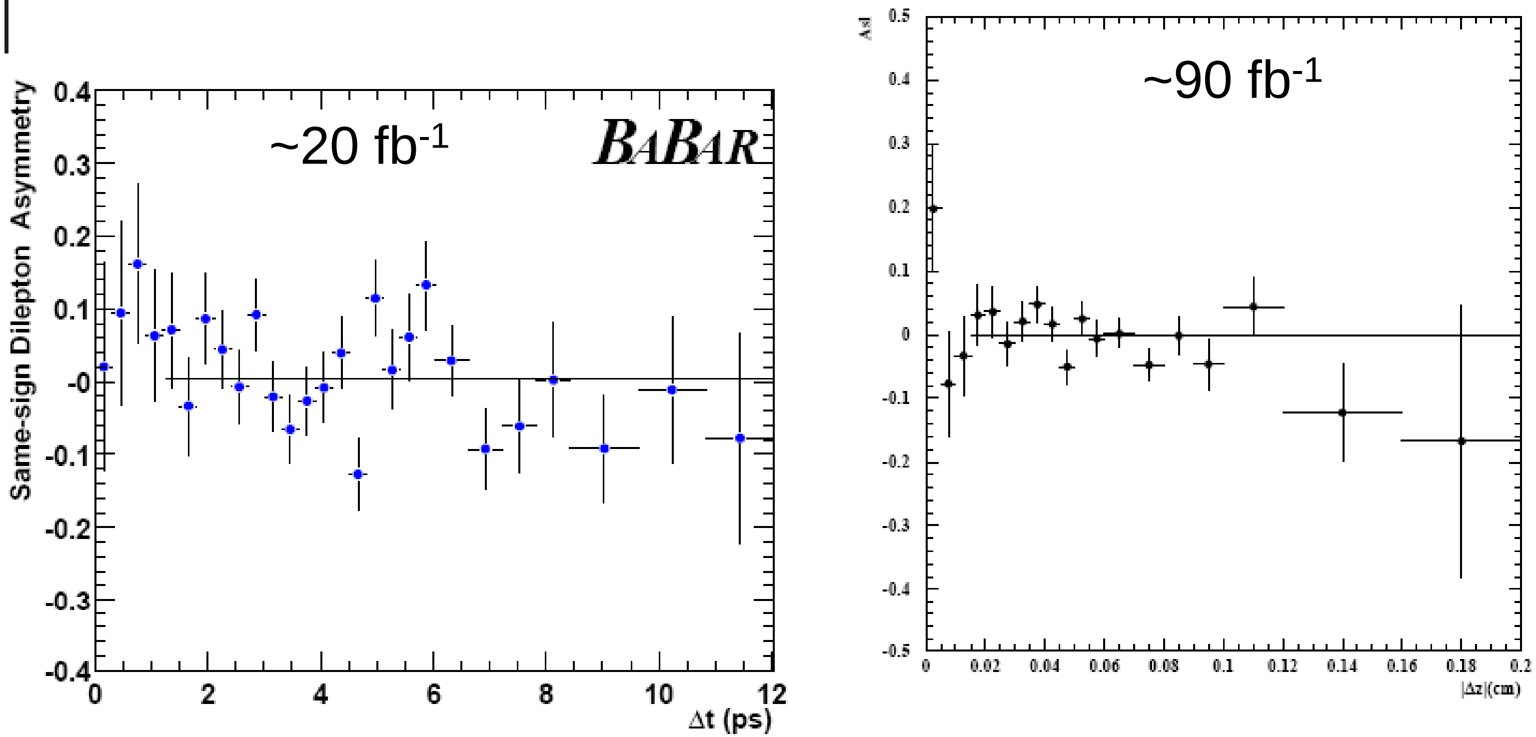
EquaL-Sign di-lepton charge asymmetry Δt dependence



Peak structure repeats itself at Larger times $\Delta t\,\Delta m = 2\pi$

$$\Delta t \Delta m \simeq 2\pi \simeq 8.2.\Gamma^{-1}\Delta m$$

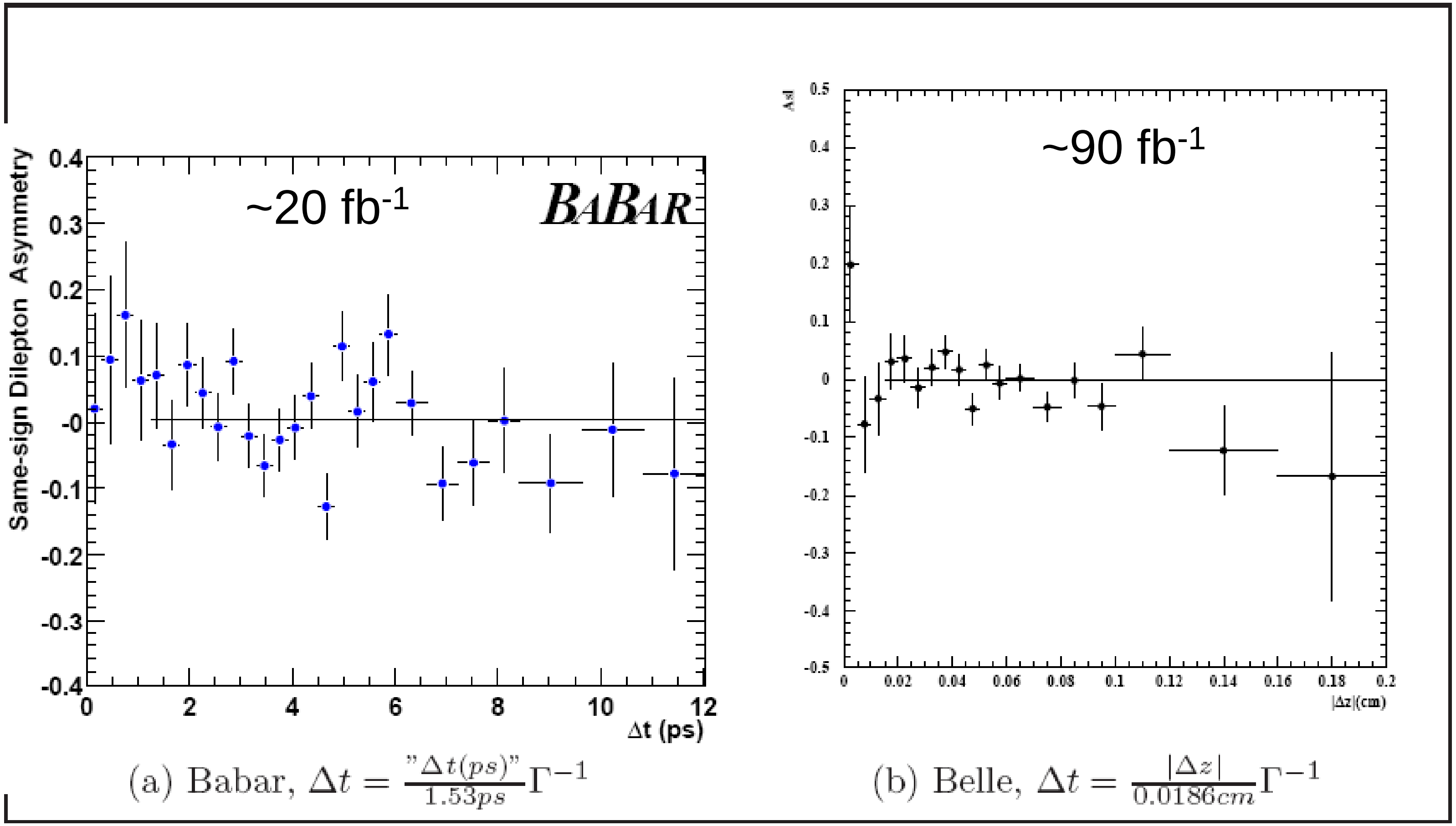
Approximate Periodicity of A_{sl} in $\Delta t\,\Delta m$: terms $\cosh(\Delta\Gamma\Delta t)$ almost constant for small $\Delta\Gamma$



(a) Babar, $\Delta t = \frac{"\Delta t(ps)"}{1.53ps}\Gamma^{-1}$ (b) Belle, $\Delta t = \frac{|\Delta z|}{0.0186cm}\Gamma^{-1}$

Figure 6.5: Reproduction of the experimental results for the A_{sl} asymmetry by Babar [36] and Belle [37] collaborations. The points for the fitting (the constant solid line in each figure) are taken for $\Delta t > 0.8\Gamma^{-1}$. As it is seen in the figures, the time independence of the A_{sl} asymmetry, as well as its fitting, have not arrived yet to a definite conclusion. Notice also that the ω-effect predicts a second peak at $\Delta t \approx 8.2\Gamma^{-1}$ ($\Delta z \approx 0.15\,cm$, $\Delta t \approx 12.4\,ps$) which the data cannot discard; see Fig. (6.3b) and text therein.

From
E. Alvarez PhD thesis



$$A_{sl}^{exp} = 0.0019 \pm 0.0105$$

[Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

$$-0.0084 \leq \Re\omega \leq 0.0100 \quad \text{at } 95\% \text{ C.L.}$$

3) Tests of Lorentz invariance and CPT symmetry in the neutral B meson system

CPT and Lorentz invariance violation (SME)

Kostelecky et al. developed a phenomenological effective model providing a framework for CPT and Lorentz violations, based on spontaneous breaking of CPT and Lorentz symmetry, which might happen in quantum gravity (e.g. in some models of string theory)

Standard Model Extension (SME) [Kostelecky PRD61, 016002, PRD64, 076001]

CPT violation in neutral B mesons according to SME:

- CPTV only in mixing, not in decay, at first order
- **z cannot be a constant** (momentum dependence)

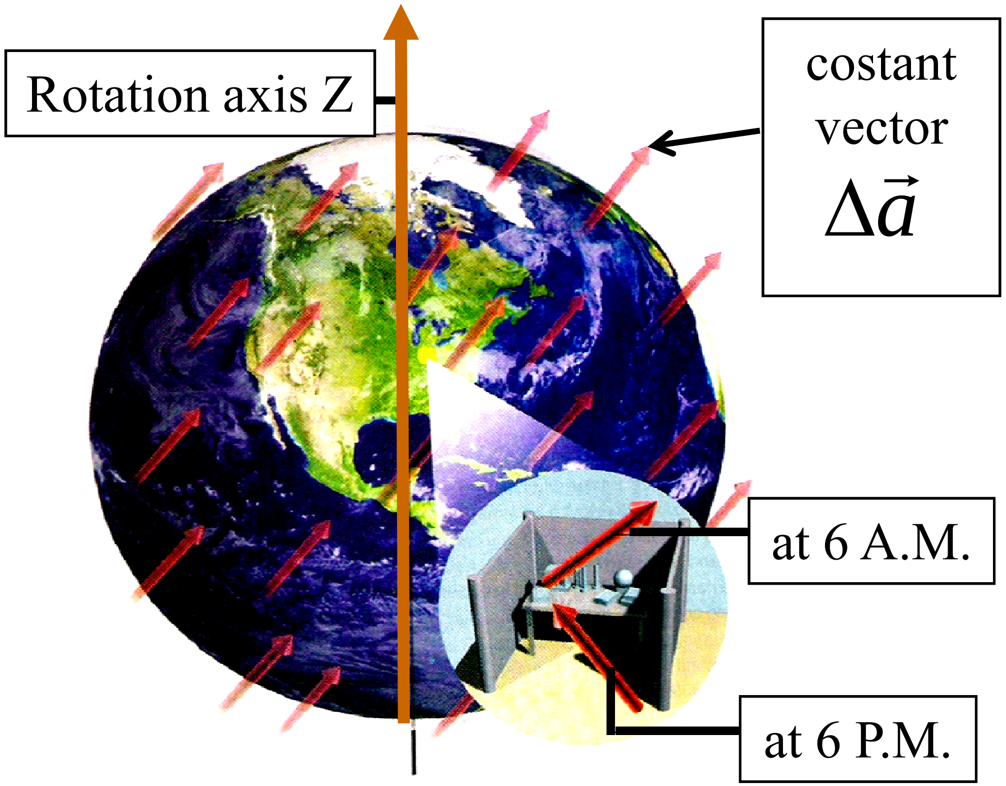
$$z = \frac{\gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a}\right)}{\Delta m - i\, \Delta\Gamma / 2}$$

where Δa_μ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.

CPT and Lorentz invariance violation (SME)

z depends on sidereal time t since laboratory frame rotates with Earth

$$\beta^{\mu}\Delta a_{\mu} = \gamma_K \left[\Delta a_0 + \beta_K \Delta a_Z \cos\chi + \beta_K \Delta a_Y \sin\chi \sin\Omega t + \beta_K \Delta a_X \sin\chi \cos\Omega t\right]$$

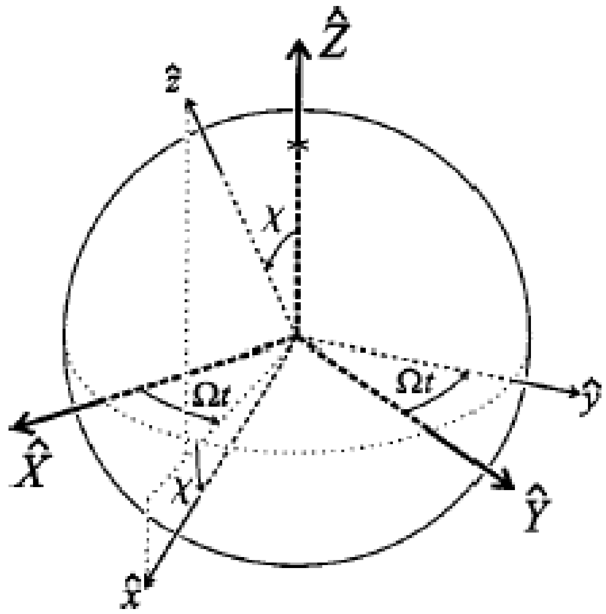


Ω: Earth's sidereal frequency

χ : angle between the z lab. axis and the Earth's rotation axis

CPT and Lorentz invariance violation (SME)

z depends on sidereal time t since laboratory frame rotates with Earth



$$\beta^{\mu}\Delta a_{\mu} = \gamma_K \big[\Delta a_0 + \beta_K \Delta a_Z \cos\chi + \beta_K \Delta a_Y \sin\chi \sin\Omega t + \beta_K \Delta a_X \sin\chi \cos\Omega t\big]$$

(in general z lab. axis is non-normal to Earth's surface)

$$z = z_0 + z_1 \cos(\Omega t + \phi)$$

Ω: Earth's sidereal frequency
χ : angle between the z lab. axis and the Earth's rotation axis

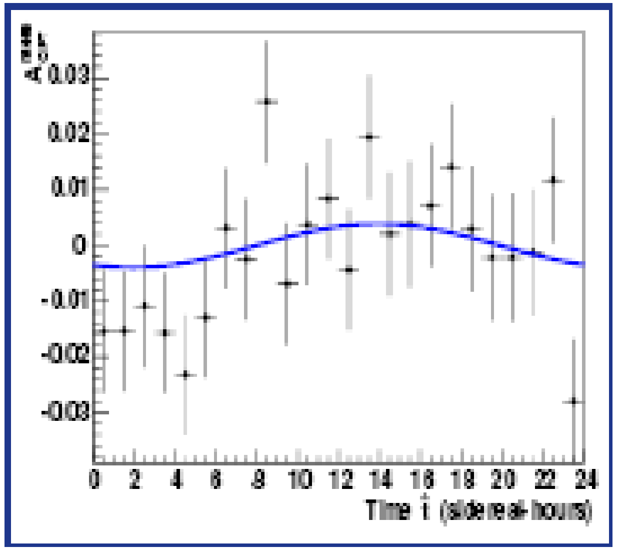
CPT and Lorentz invariance violation (SME)

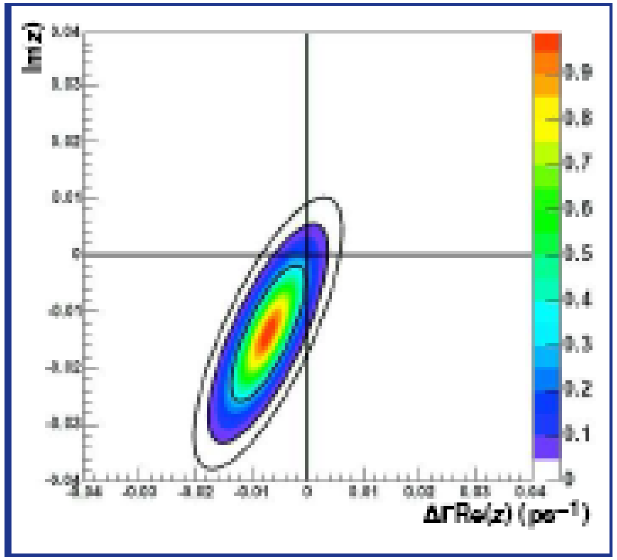
CPT & Lorentz Viol. with Dileptons | BABAR | $232\ \mathrm{fb}^{-1}$ | PRL 100, 131802 (2008)

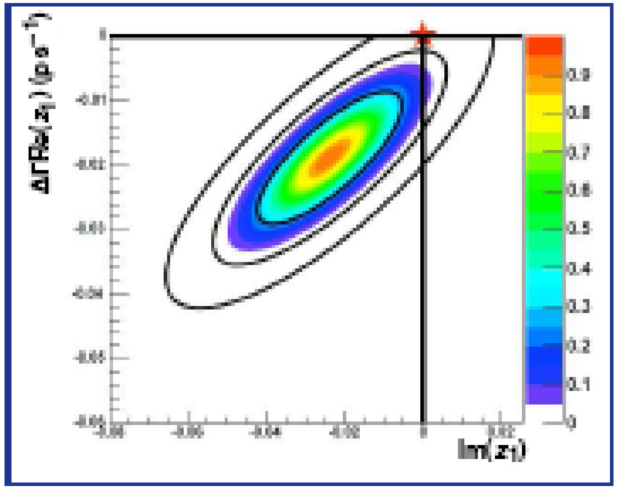
- *CPT* violation in SM Lorentz violating extension (SME): **V.A.Kostelecky, Phys.Rev.D,64,076001,2001**
- $z \simeq \dfrac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$ with
  - $\beta^\mu = (\gamma, \gamma\vec{\beta})$ B velocity in LAB ($\approx \Upsilon(4S)$ velocity along boost)
  - $\Delta a_\mu = r_{q_1} a_\mu^{q_1} - r_{q_2} a_\mu^{q_2}$ constant 4-vector w.r.t. Sun rest frame
  - q_i = meson quarks, r_{q_i} = quark-binding and normalization
- $\beta^\mu \Delta a_\mu$ is real $\Longrightarrow \mathrm{Im}(z) = \dfrac{\Delta\Gamma}{2\Delta m}\mathrm{Re}(z) \ll \mathrm{Re}(z)$
- $\beta^\mu \Delta a_\mu = \gamma\left[\Delta a_0 - \beta\Delta a_Z \cos\chi - \beta\sin\chi\left(\Delta a_Y \sin\widehat{\Omega t} + \Delta a_X \cos\widehat{\Omega t}\right)\right]$
  - χ = angle between BABAR boost and earth rotation axis, $\cos\chi \simeq 0.628$, $\beta\gamma \simeq 0.55$
- $z = z_0 + z_1 \cos(\widehat{\Omega t} + \phi)$ sidereal time changes angle between Δa_μ and β^μ
- measure $A_{CPT/CP}$ as before but as function of sidereal time, searching for periodic variations

CPT and Lorentz invariance violation (SME)

CPT & Lorentz Viol. with Dileptons — BABAR — $232\ \mathrm{fb}^{-1}$ — PRL 100, 131802 (2008)







- $e^+e^- \to \mu^+\mu^-$ events used as control sample without *CPT* violation
- no evidence for z variation with sidereal time or period (2.8σ away from zero)
  - no evidence for signal also at $\sim 20k$ other tested frequencies
- $\mathrm{Im}z_0 = [-5.2 \pm 3.6\,(\mathrm{stat.}) \pm 1.9\,(\mathrm{syst.})]\cdot 10^{-3}$ $\quad$ $\mathrm{Im}z_1 = [-17.0 \pm 5.8\,(\mathrm{stat.}) \pm 1.9\,(\mathrm{syst.})]\cdot 10^{-3}$
  - largest systematics from understanding of SVT alignment, z absolute scale, PDF resolution

CPT and Lorentz invariance violation (SME)

Babar [PRL 100 (2008) 131802]

$$\Delta a_0 - 0.30\Delta a_Z \cong (-3.0 \pm 2.4)(\Delta m / \Delta\Gamma)\times 10^{-15} \text{ GeV}$$

$$\Delta a_X \cong (-22 \pm 7)(\Delta m / \Delta\Gamma)\times 10^{-15} \text{ GeV}$$

$$\Delta a_Y \cong \left(-14^{+10}_{-13}\right)(\Delta m / \Delta\Gamma)\times 10^{-15} \text{ GeV}$$

i.e. $\Delta a_{x,y}$, $(\Delta a_0 - 0.30\ \Delta a_Z) \sim O(10^{-13}\text{ GeV})$

KLOE preliminary

In kaons (different param.):

$$\Delta a_0^K = (0.4 \pm 1.8)\times 10^{-17} \text{ GeV}$$

$$\Delta a_X^K = (-6.3 \pm 6.0)\times 10^{-18} \text{ GeV}$$

$$\Delta a_Y^K = (2.8 \pm 5.9)\times 10^{-18} \text{ GeV}$$

$$\Delta a_Z^K = (2.4 \pm 9.7)\times 10^{-18} \text{ GeV}$$

KTeV : Δa_X^K, $\Delta a_Y^K < 9.2 \times 10^{-22}$ GeV @ 90% CL

4) Future plans

Prospect for SuperB

Test of	Param.	Present best measurement	SuperB L~50 ab^{-1}
CPT	Re z	0.00± 0.12	$\pm 0.3 \times 10^{-3}$
CPT	Im z	$(-13.9 \pm 7.8) \times 10^{-3}$	$\pm 0.6 \times 10^{-3}$
QM	ζ_{00}	$(2.9 \pm 5.7) \times 10^{-2}$	$\pm 3.6 \times 10^{-3}$
QM	ζ_{SL}	$(0.4 \pm 1.7) \times 10^{-2}$	$\pm 1 \times 10^{-3}$
CPT & QM	α,β,γ		
CPT & EPR corr.	Re(ω)	<0.01	$\pm 4 \times 10^{-4}$
CPT & EPR corr.	Im(ω)		
CPT & Lorentz	$\Delta a_0 - 0.3 \Delta a_Z$	$(-3.0 \pm 2.4) \times \Delta m/\Delta\Gamma \times 10^{-15}$ GeV	$\pm 1.5 \times \Delta m/\Delta\Gamma \times 10^{-16}$ GeV
CPT & Lorentz	Δa_X	$(-22 \pm 7) \times \Delta m/\Delta\Gamma \times 10^{-15}$ GeV	$\pm 4.4 \times \Delta m/\Delta\Gamma \times 10^{-16}$ GeV
CPT & Lorentz	Δa_Y	$(-14 \pm 12) \times \Delta m/\Delta\Gamma \times 10^{-15}$ GeV	$\pm 7.6 \times \Delta m/\Delta\Gamma \times 10^{-16}$ GeV

Conclusions

- Neutral meson systems are excellent laboratories for the study of CPT symmetry and the basic principles of Quantum Mechanics;
- Several parameters have been recently measured in B and K systems, in same cases (K) with a precision reaching the interesting Planck's scale region;
- All results are consistent with no CPT violation and no QM violation
- The K and B systems are very similar but CPT/QM effects may appear differently in the two systems (e.g. energy dependence)=> it's worth improving the precision of the tests in both systems.

- For B mesons a SuperB could improve the statististal uncertainty on several parameters by about one order of magnitude.

- For kaons KLOE (KLOE-2) is restarting (end 2009) ; improvement of precision by one order of magnitude in run phase-2.